ESTCP
Cost and Performance Report

(WP-201317)

Demonstration of Novel Sampling Techniques for Measurement of Turbine Engine Volatile and Non-volatile Particulate Matter (PM) Emissions

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14. ABSTRACT

This project consists of demonstrating the performance and viability of two devices to condition aircraft turbine engine exhaust to allow the accurate measurement of total (volatile and non-volatile) particulate matter (PM) emissions by promoting condensation of volatile species. A device to separate volatile from non-volatile species from turbine engine exhaust was also evaluated for the measurement of only non-volatile PM. These measurements are needed to assess the environmental burden of military aircraft for regulatory purposes. Non-volatile PM are those found at the engine exit temperature and pressure conditions, whereas volatile PM are those formed from organic and sulfur compounds via gas-to-particle reactions in the atmosphere. The total PM devices were evaluated by comparing the PM characteristics to those found in plume samples using exhaust from a T63 turboshaft and an F117 turbofan engine. Results show that the devices can partially simulate the thermophysical processes in the plume that lead to the formation of volatile PM. However, several of the performance criteria for these devices were not met. A vapor particle separator met the performance goals and shall be considered for non-volatile PM systems after further evaluations.

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Turbine engine emissions, non-volatile and volatile PM, PM environmental regulations

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COST & PERFORMANCE REPORT
Project: WP-201317

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

ACRONYMS AND ABBREVIATIONS

AFRL	Air Force Research Laboratory
AIR	Aerospace Information Report
AMS	Aerosol Mass Spectrometer
ARI	Aerodyne Research Inc.
ARP	Aerospace Recommended Practice
CDP	Condensation Dilution Probe
CFD	Computational Fluid Dynamics
CPC	Condensation Particle Counter
CVS	constant volume sampling
DC	Dilution Chamber
DoD	Department of Defense
EC/OC	Elemental Carbon/Organic Carbon
EEPS	Engine Exhaust Particle Sizer
EERF	Engine Environment Research Facility
EI_n	Particle Number Emission Index
EPA	Environmental Protection Agency
ICAO	International Civil Aviation Organization
m	Meter(s)
MAAP	Multi-Angle Absorption Photometer
NAAQS	National Ambient Air Quality Standards
NDIR	Non-Dispersive Infrared
NIOSH	National Institute for Occupational Safety and Health
nm	nanometer
NRMRL	National Risk Management Research Laboratory
ORNL	Oak Ridge National Laboratory
PM	Particulate Matter
PMP	Particulate Matter Programme
PN	Particle Number
PTR-MS	Proton Transfer Reaction -Mass Spectrometry
SAE	Society of Automotive Engineers

SAEPA	Simulated Aircraft Exhaust Plume Aging
SBIR	Small Business Innovative Research
SMPS	Scanning Mobility Particle Sizer
UDRI	University of Dayton Research Institute
μm	Micrometer
VPR	Volatile Particle Remover
VPS	Vapor Particle Separator
WPAFB	Wright-Patterson Air Force Base

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The efforts of John Storey, Scott Curran, Teresa Barone, Steve Allman, Brian Bischoff and Shannon Mahurin of Oak Ridge National Laboratory (ORNL) to develop the Vapor Particle Separator (VPS) during this and SERDP project WP-1627 are greatly appreciated. Also, the work of Erik Kabela (also from ORNL) in support of the demonstration on the C-17 is acknowledged.

The condensation dilution probe (CDP) was developed under an Air Force Small Business Innovation Research (SBIR) contract (contract number: FA9101-08-C-0013), and the support of Robert Howard, the AEDC SBIR technical monitor, is greatly appreciated.

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

The objectives of this project are to demonstrate the performance and viability of three devices to condition aircraft turbine engine exhaust for the measurement of non-volatile and total (volatile and non-volatile) particulate matter (PM) emissions. These measurements are needed to assess the environmental burden of military and commercial aircraft to verify compliance with future regulations. Non-volatile PM are those found at the engine exit conditions, whereas volatile PM are those formed in the atmosphere from organic and sulfur exhaust compounds. Accurate measurement of turbine engine non-volatile PM is challenging due to a number of factors, including: (1) difficulty of sampling in the harsh environment found at the engine exit, (2) particle losses in the sample lines, (3) PM physical and chemical transformations as it is transported to the instrumentation. Measurements of volatile PM are even more difficult as these are formed in the exhaust plume and are influenced by fuel, ambient conditions and the volatile species composition.

TECHNOLOGY DESCRIPTION

Two devices, a dilution chamber (DC) and a condensation dilution probe (CDP), were evaluated to assess their effectiveness to condition turbine engine exhaust for total PM emissions measurements. Both were designed to promote the condensation of volatile species, which can then be characterized along with non-volatile PM using conventional aerosol instruments. The third device, a vapor particle separator (VPS) used to separate volatile and non-volatile species, was evaluated to support the measurement of only non-volatile PM. The performance of the VPS was assessed in the laboratory by using tetracontane (C_{40}) particles and during field demonstrations using exhaust from two turbine engines (T63 and PW-F117).

DEMONSTRATION RESULTS

PM physical and chemical properties were measured at the exit of the condensation devices at several engine settings, and compared to measurements made in the exhaust plume. Data show that the devices promoted the formation of volatile PM, therefore simulating ambient gas-to-particle processes. However, the concentration of particles formed was significantly lower than those found at plume locations, especially when the engine was operated with high sulfur content fuel. Since neither condensation device met all of the performance objectives set for the project, it is concluded that these technologies are not currently ready to use for compliance relevant measurements. Based on the set performance criteria, the VPS met the objectives of the project. Evaluations against the criteria set by the Society of Automotive Engineers (SAE) E31 committee Aerospace Recommended Practice (ARP) 6320 for volatile particle removers (VPR) shall follow to further validate its use for non-volatile PM measurement.

IMPLEMENTATION ISSUES

Pending further improvements and successful performance demonstrations, the implementation issues for these devices are relatively minor since the sampling system from engine to device is the same as those existing for gaseous emissions and smoke number certification of engines.

Additions include the dilution device, sampling lines for the sample after conditioning, and the PM characterization instruments. Regarding the VPS, implementation issues are minimal and believed to be simpler than the use of the Volatile Particle Remover (VPR) systems considered presently by the SAE E31 committee.

1.0 INTRODUCTION

1.1 BACKGROUND

Due to its harmful environmental and health impacts, particulate matter (PM) [specifically particles less than 10 and 2.5 micrometers (μm) in aerodynamic diameter (PM10 and PM2.5)], have been identified as criteria pollutants [1]. Both PM10 and PM2.5 include volatile and non-volatile PM (defined below) emitted from mobile and stationary sources. Accordingly, the U.S. Environmental Protection Agency (EPA) and international environmental agencies continue to implement more stringent air quality standards to limit PM emissions. In regions that do not meet the National Ambient Air Quality Standards (NAAQS) requirements, the individual states need to develop and adopt strategies to be included in their EPA-mandated State Implementation Plan (SIP) to bring the area into compliance. Within the SIP, states must develop measures to control and reduce emissions, and demonstrate compliance with the NAAQS within five years of being designated as nonattainment. In the aviation sector, these measures may include: changing airport operations (e.g., surface congestion management strategies), replacing or modifying ground support equipment, infrastructure additions (e.g., air traffic control, runways) and others. Although current aircraft turbine engines are substantially less polluting than legacy engines manufactured pre-1980s (as evidenced by the less visible smoke trail), they still emit significant quantities of very fine volatile and non-volatile particles (PM2.5). Consequently, current and future PM regulations will likely affect the aviation sector by slowing down the growth of commercial aviation worldwide and negatively impact military operations by limiting readiness exercises and restricting the use of different types of aircraft. In the military, high fines may be incurred due to non-compliance of environmental regulations. Evidently, it is imperative that accurate and reliable aircraft turbine engine measurement techniques are developed for total (volatile + non-volatile) PM to assess the true environmental burden of aviation activities and to help determine the proper corrective action (if needed). After accurate assessments are performed, more educated decisions can be made to properly and cost-effectively control and mitigate PM emissions.

Aircraft PM is formed in the engine combustor due to incomplete combustion of fuel, and in the atmosphere through gas-to-particle transformations of organic and sulfur-based volatile components upon cooling and mixing with the atmosphere (see Figure 1). PM emitted from the engine at exit temperatures and pressures are defined as non-volatile, whereas those formed via gas-to-particle conversion in the atmosphere are known as volatile PM. Accurate measurement of non-volatile PM from aircraft engines is a daunting task due to the harsh environment found at the engine exit, particle losses during transport in sample lines, and physical and chemical transformations of the sample as it is transported to analytical instrumentation. Reliable measurements of volatile PM are even more challenging as these are formed in the exhaust plume and are greatly influenced by ambient conditions and composition of the volatile species.

Under SERDP project WP-1627, the Oak Ridge National Laboratory (ORNL)/Air Force Research Laboratory (AFRL)/University of Dayton Research Institute (UDRI) team developed a Vapor Particle Separator (VPS) to partition volatile and non-volatile components in aircraft engine exhaust and allow volatile species to be chemically analyzed. Also under this SERDP project, a Dilution Chamber (DC) was developed to homogeneously dilute and condition aircraft exhaust for measurement. Under an Air Small Business Innovative Research (SBIR) program, Aerodyne Research Inc. (ARI) developed a Condensation Dilution Probe (CDP) to effectively control the

formation of volatile particles to simulate atmospheric processing behavior and to quantify this contribution on the total PM mass emissions. All devices have shown excellent potential when testing in laboratory and limited field environments. Further demonstrations of these devices may lead to more reliable methodologies for the measurement of both volatile and non-volatile PM emissions from turbine engines, which can then be used for cost-effective determination of regional PM emissions for regulatory purposes.

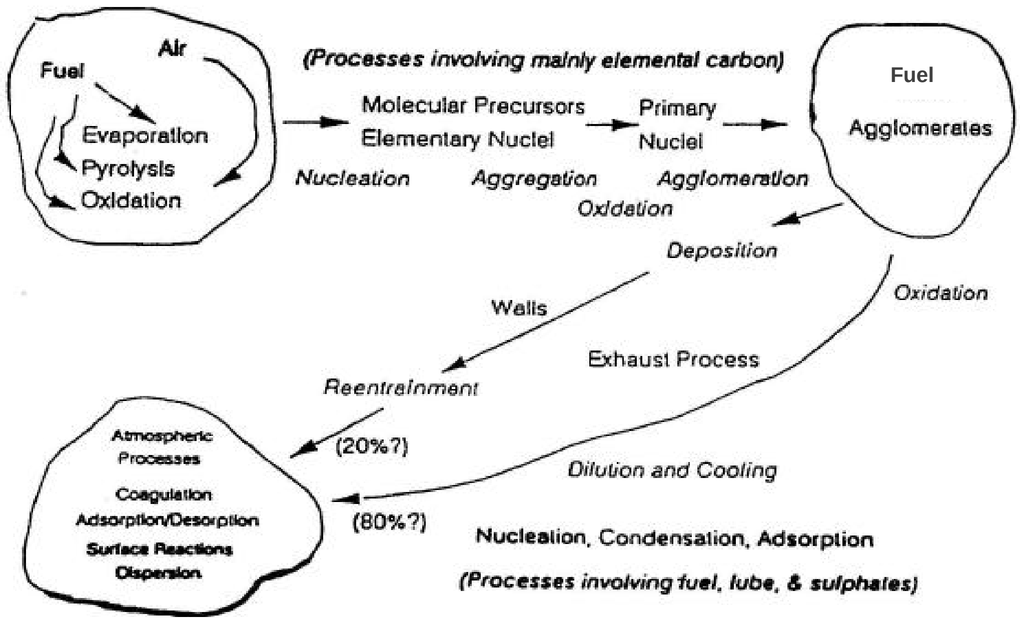

Figure 1. Formation of Volatile and Non-volatile PM from Engine Exhaust [from Ref 2]

1.2 OBJECTIVES OF THE DEMONSTRATION

The objective of the demonstration can be divided into four parts, listed below.

- Demonstrate reliable operation of the DC to condition PM sample collected at the engine exit plane for the characterization of non-volatile PM.
- Demonstrate the viability of the DC and CDP to simulate volatile PM formation in the atmosphere by comparing to a measurement conducted far field (e.g., 20 meters [m]). Successful demonstration will allow for the characterization of total PM at the exit plane.
- Demonstrate efficient operation and establish conditions of the VPS to remove volatile PM precursors from turbine engine exhaust. Successful demonstration may lead to inclusion of the VPS in the non-volatile Aerospace Recommended Practice (ARP) as a more efficient alternative to the available commercial volatile particle remover (VPR) units.
- Develop sampling methodology with the most efficient devices and provide recommendations to Society of Automotive Engineers (SAE) E-31 for potential inclusion in the non-volatile PM number and mass ARP. Develop an Aerospace Information Report (AIR) as a first step towards the development of an ARP for total (volatile and non-volatile) turbine engine PM measurements.

1.3 REGULATORY DRIVERS

The EPA has promulgated the NAAQS for $PM_{2.5}$, which impacts air operations at Department of Defense (DoD facilities and thus, squadron basing options. Each facility must perform a conformity analysis which shows that the emissions from that facility do not violate the $PM_{2.5}$ ambient air quality standard. Since $PM_{2.5}$ includes both volatile and non-volatile PM components, methods which allow for quantification of the contribution of each to the total PM are necessary. At the present time, no such information exists for military aircraft and thus new data and methodologies to obtain these data are needed.

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2.0 DEMONSTRATION TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

This program consists of demonstrating the viability of three devices to condition turbine engine exhaust for the analysis of non-volatile and total (volatile and non-volatile) PM emissions. The technologies (devices) are described below.

2.1.1 DC

PM measurements in diesel engines are conducted using full-flow Constant Volume Sampling (CVS) systems, which dilute and condition the entire engine sample to simulate PM dilution processes in the atmosphere. Because of the significantly higher exhaust mass flows and gas velocities, this approach is not feasible for turbine engines. For turbine engine PM sampling, the historical approach has been to sample a portion of the flow near the exhaust nozzle and dilute at the probe-tip with nitrogen. Although this methodology is believed to provide a good representation of the non-volatile PM emissions, it is complex and sample dilution downstream of the engine exit is preferable as engine manufacturers can use existing gas probes and rakes. The DC in this project was designed to promote condensation and thus, the formation of volatile particles (simulating ambient dilution), which can then be characterized using conventional aerosol instruments. The DC (Figure 2) has a cylindrical design with three regions: exhaust sample injection and primary dilution zone (via an ejector and motive flow), a secondary diluent zone, and a turbulent mixing zone. Raw exhaust is extracted at the engine exit plane and drawn to the DC by the ejector. Compressed ambient air or nitrogen is used as the motive (driver) flow. The sample is then diluted with compressed nitrogen or ambient air drawn into the DC with a variable speed blower. The mixing section downstream of the ejector is comprised of a converging/diverging section and a homogeneous sampling zone. The converging/diverging section promotes convective mixing of the sample and diluent streams to overcome diffusional transport limitations. The DC has an internal diameter of 0.21 m with a cylindrical inlet length of 0.80 m. The internal diameter then rapidly converges to 0.038 m followed by a gradual divergence to the original diameter over the next 0.10 m. The diluted sample extraction point is located approximately 1.10 m downstream of the converging/diverting section throat.

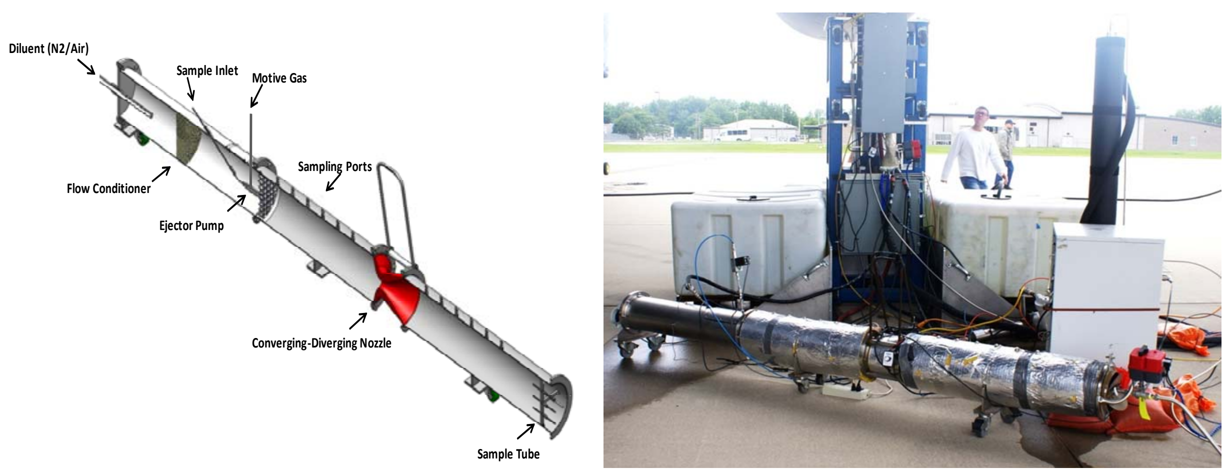


Figure 2. Schematic of DC and Implementation of DC during C-17 Demonstration

2.1.1 VPS

A new generation of volatile PM thermal separation device was designed and tested at ORNL during the earlier SERDP WP-1627 project. In the VPS construction, a microporous metallic membrane was used to separate vapors and particles [3]. The metallic membrane is chemically inert and similar to that used in a previous study of water treatment [4]. The membrane is fabricated as double-layered from 306L stainless steel, and is about 400 µm thick when two layers are combined. The VPS uses a cross-flow membrane separation concept filtration design to remove vapors and prevent re-condensation of desorbed vapor onto existing particles. Once particles are desorbed in the heated section, they are removed via preferential diffusion through the porous membrane via pressure and concentration differential. The collected vapors can be subsequently analyzed for chemical composition. This is a new capability not available in current thermodenuder or catalytic strippers that have been used as volatile particle removers. Figure 3 shows a schematic of the main components of the VPS. The engine sample enters the VPS through the heating section, which is followed by a section for separation of desorbed volatile species from the non-volatile PM. The volume between the metallic membrane and the tube serves as a temporary holding space for the desorbed vapors before they are evacuated by an extraction pump, which leaves no opportunity for the vapor to re-enter the membrane and condense on the non-volatile PM or nucleate into new ones.

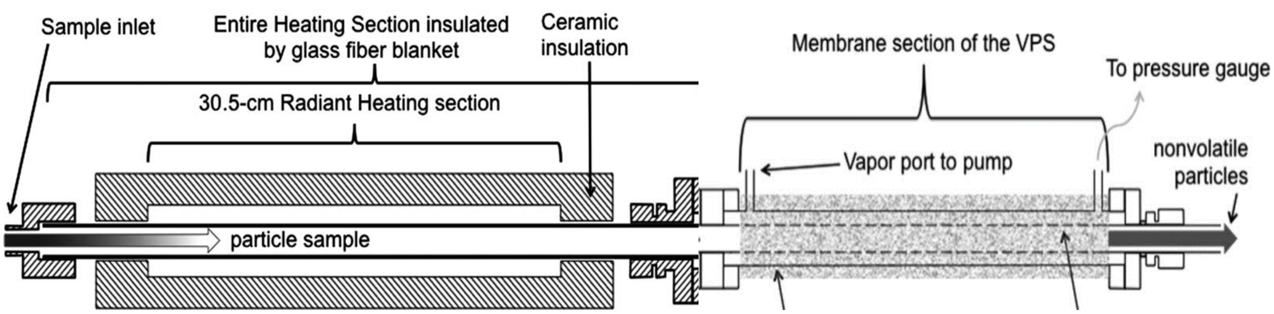
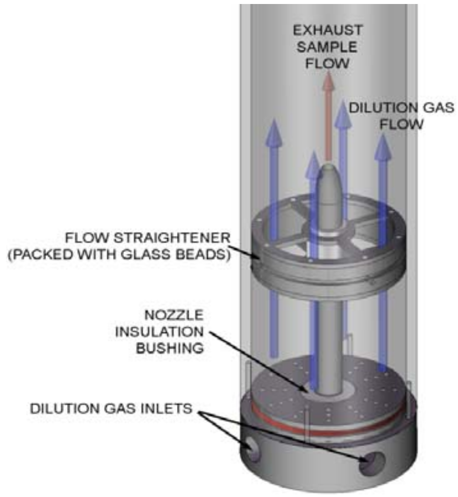


Figure 3. Schematic of the VPS

2.1.2 CDP

The CDP was developed by ARI under an Air Force SBIR project. Its objective is to simulate the environmental conditioning and volatile species condensation of volatile species in a controlled manner when extracting exhaust from the engine exit plane [5]. The CDP (referred in references as Simulated Aircraft Exhaust Plume Aging (SAEPA) probe has been demonstrated in the laboratory test environments and sampling turbine engine exhaust on the tarmac at airports. Shown schematically in Figure 4, the device extracts exhaust gas from the engine exit plane, and transfers the sample through a heated (> 150°C) stainless steel tube to a dilution and aging chamber. Transferring the sample through a heated tube is required to prevent microphysical reactions as well as thermophoretic loss of soot particles. The raw exhaust sample is injected as a turbulent jet into the chamber at the centerline, and the dilution gas (either nitrogen or CO2 -free air) is introduced as a sheath co-flow. The exhaust is injected as a turbulent jet into a laminar dilution co-flow to mimic the jet engine plume traveling through the ambient air, minimizes the effect of the chamber wall during the critical microphysical processes, and produce a well defined flow.

The dilution gas is conditioned to achieve the desired temperature and relative humidity prior to introduction to the chamber, and passes through a packed-bed flow straightener to provide uniform plug-flow. Within the chamber, the exhaust sample and dilution gas mix in a well-defined manner.



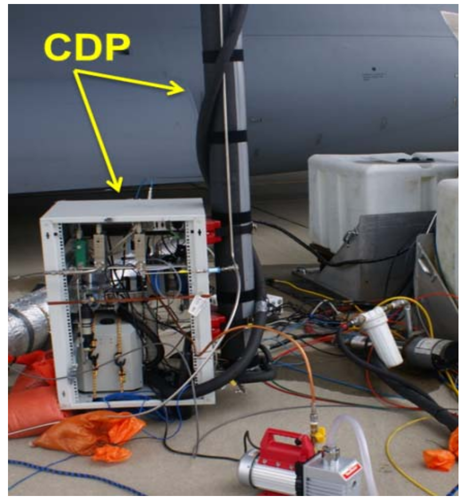


Figure 4. Schematic of the Inlet of the CDP and CDP Hardware Used during C-17 Demonstration

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Although a standard practice for the measurement of total turbine engine PM has not been established, based on current understanding it requires sampling the engine exhaust at a sufficient distance downstream from the engine to allow the volatile species to cool/dilute in the plume and nucleate into particles that can be characterized. This approach requires additional probes and sample lines, and is not practical for characterizing engines in most test facilities. Moreover, this practice is not desired as the measured PM concentrations can fluctuate significantly due to the ambient sampling conditions (e.g., temperatures, wind direction, humidity) during the tests. The approach in this demonstration has the potential to significantly simplifying the total PM sampling by conditioning the sample with ambient air in a controlled manner near the engine to obtain a sample similar to one found far field (20-30 m) from the engine. The limitations with the dilution devices include: lack of sufficient condensation of volatile compounds or condensation of volatiles on the surface of devices. Control of the formation of volatile PM is difficult as it is a strong function of the concentration and composition of the volatile species and environmental conditions (e.g., overall dilution, humidity, etc.). The secondary dilution flows were varied to assess their impacts on volatile condensation. Real-time particle number (PN) and size distribution measurements will be used to determine the degree of volatile specie condensation and thus, volatile particle formation. Condensation and loss of particles to the wall are reduced by heating the DC to 75°C with currently installed heat blankets and increasing the diluent concentration. In the demonstration and validation of the condensation devices, a potential risk area (or limitation) is the collection of reliable/repeatable PM emissions data at the downstream plume sample location since atmospheric conditions greatly influence PM characteristics. Risk was reduced by increasing test times (when possible) to gather statistically significant data for proper analysis.

For the non-volatile characterization, the VPS has the advantage over commercial Volatile Particle Remover (VPR) units in its simple operation, lower cost and potential to analyze the removed volatile species. The limitation may be in the potential of fouling of the metallic membrane and reduced separation efficiency with time.

3.0 PERFORMANCE OBJECTIVES

The performance objectives, success criteria (as defined at project start) are provided in Table 1.

Table 1. Project Performance Objectives

Performance Objective	Data Requirements	Success Criteria	Results
Demonstrate volatile species condensation (volatile PM formation) in the DC and CDP. Significant increase in PM compared to probe-tip dilution.	Particle size distributions for samples collected at engine exit, 30 m and at DC and CDP.	Clear evidence of volatile particle formation in DC and CDP compared to tip-dilution. 10X increase in 5-20 nanometer (nm) particle number (PN).	• *Met 1st criteria.* Evidence of volatile PM formation. • *Did not meet 2nd criteria.* Only 2-5X increase in 5-20 nm size particles.
Demonstrate similar PM chemical characteristics for samples collected at the DC, CDP and 30 m locations.	Particle chemistry and gaseous organics using Aerosol Mass Spectrometer (AMS) and Proton Transfer Reaction -Mass Spectrometry (PTR-MS)	Composition of PM from DC or CDP and plume sample within ±25% in absolute or normalized terms.	*Criteria met.* Same % organics in plume and condensation devices.
Demonstrate that ambient air diluted samples in the DC and CDP produce similar total PM characteristics as at the 30 m sampling location	Particle size distributions, total mass and total particle concentrations	±40% of the PN ±30% mass ±25% of mean diameter	*Criteria only met for some conditions. Not consistent.*
Demonstrate that N_2 diluted samples in the DC and CDP produce similar non-volatile PM characteristics as non-volatile sample	Particle size distributions and total particle concentrations	±25% of the PN ±15% of mean diameter	Limited evaluations performed. *Criteria met for some conditions.*
Demonstrate efficient performance of the VPS to remove tetracontane particles	Particle size distributions and total particle concentrations	> 99 % vaporization of 15 nm tetracontane particles, with an inlet concentration of >10,000 cm^{-3}.	*Criteria met.*
Demonstrate efficient performance of the VPS to remove volatile species from engine PM	Particle size distributions and total particle concentrations	Qualitative data. Significant reduction in 15nm and smaller particles and increase on mean particle size	*Criteria met.* Removed both volatile and non-volatile engine PM. Recommend further evaluations at lower temperatures.

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4.0 SITES/PLATFORM DESCRIPTION

4.1 TEST PLATFORMS/FACILITIES

Two turbine engines representing legacy and newer technologies were used in this demonstration program.

4.1.1 T63 Turboshaft Engine at Wright-Patterson Air Force Base (WPAFB), OH

Tests on a T63 turboshaft helicopter engine were conducted to increase understanding into the formation, composition and measurement of volatile species/PM and to characterize and demonstrate the performance of the condensation devices and VPS in a controlled environment. This engine provided the opportunity to vary fuel chemical composition (e.g., sulfur and aromatic content) to influence the concentration of volatile PM precursors. The engine is located in the Engine Environment Research Facility (EERF) in the Aerospace Systems Directorate at WPAFB.

4.1.2 PW-F117 Turbofan Engine at WPAFB, OH

The second demonstration was on a C-17 aircraft engine. The PW-F117 engine is the military variant of the Pratt & Whitney PW2000 commercial engine, which powers the Boeing 757-200 aircraft. The test site was at the 445th Air Lift Wing at WPAFB.

4.2 PRESENT OPERATIONS

Currently, PM emissions from aircraft turbine engines are evaluated by the engine manufacturer by measuring smoke number (SAE ARP 1179) during the engine certification process. Due to the cleaner burning engines and lack of compliance-type quantitative information, the smoke number is inadequate for measuring PM2.5 emissions from new turbine engines. Therefore, more advanced techniques are needed to assess commercial and military aircraft PM environmental burden.

4.3 SITE-RELATED PERMITS AND REGULATIONS

The demonstration team consulted with safety and environmental officials to comply with all EPA and base required site-related permits and regulations during the demonstration activities.

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5.0 TEST DESIGN

Test engines were operated at several power settings to demonstrate operation of the dilution devices and VPS under a wide range PM levels. The engines were sampled at steady state, and tested sufficiently long to ensure statistical significance of the data. Samples were extracted with multiple probes at the engine exit plane (<1 m) and far field (20 m - plume). Raw samples in the DC and CDP were diluted to dilution ratios measured at the plume. Comparison of PM characteristics (number and size) of sample diluted at probe-tip (or using an ejector diluter and secondary dilution), and the sample from the DC, CDP were conducted. The test plans for the T63 and PW-F117 engine demonstrations are provided in Table 2.

Table 2. Test Matrix for the Demonstrations on T63 and PW-F117 Engines

Engine	Engine Condition	Fuel	Sampling Device or Location	Dilution Ratio at Devices
T63	• Idle • Cruise	• JP-8 • JP-8+aromatics (25% total) • JP-8+Sulfur (3000 ppm total)	• Probe-tip diluted (engine exit) • DC (engine exit) • CDP (engine exit) • Plume	• Same as Plume • 2X Plume
PW-F117	• Idle • 20% rated thrust • 33% rated thrust	F-24 (Jet A + military additives)	• Ejector-diluted (engine exit) • DC (engine exit) • CDP (engine exit) • Plume	Same as Plume

The suite of PM and gaseous emissions instrumentation for these evaluations is shown in Table 3. PM was sampled and characterized at both the engine exit plane (non-volatile) and far field and at the exit of the VPS and condensation devices. A primary goal of this effort is to improve the understanding of processes which affect volatile PM formation and develop viable techniques for measurement of total and volatile PM emissions from turbine engine aircraft.

The AFRL/UDRI team performed PM and gaseous emissions measurements at the engine exit plane, plume and condensation devices. ORNL performed non-volatile PM measurements using a modified- Particulate Matter Programme (PMP) volatile particle remover (VPR) system to compare to and assess the VPS performance. The U.S. EPA National Risk Management Research Laboratory (NRMRL) team performed characterization measurements of the volatile and non-volatile PM as well as the gas-phase precursors in the condensation devices for comparison to those observed at the plume sampling location. ARI in collaboration with Montana State University (MSU), performed measurements of PM and gaseous species for the plume and diluted samples from the condensation devices. Chemical composition of volatile PM and gaseous organic species were measured using mass spectroscopic techniques. Total PN and light extinction were measured with optical techniques.

Table 3. Instrumentation, Measurements and Sampling Locations

Instrument / Method	Measurement	Sampling Location	T63 Engine	PW-F117 Engine
Condensation Particle Counter (CPC) (Several models)	PN	1 m (probe-tip or two-stage dilution), DC, CDP, VPS, VPR, plume	**x**	**x**
Scanning Mobility Particle Sizer (SMPS) (TSI 3936)	Particle Size Distribution (D=4.0 - 570 nm)	1 m (probe-tip or two-stage dilution), DC, CDP, VPS, VPR, plume	**x**	**x**
Multi-Angle Absorption Photometer (MAAP) (Thermo 5012) (T63 only)	Black Carbon Mass	DC, CDP, plume	**x**	**-**
Laser Induced Incandescence	Black Carbon Mass	DC CDP, plume	**-**	**x**
AMS	PM chemical speciation (organics, sulfate, nitrates)	DC, CDP, plume	**x**	**x**
Proton-Transfer Reaction Mass Spectrometer	Volatile organic species	DC, CDP, plume	**-**	**x**
FTIR Analyzer (MKS 2030)	CO_2, CO, NO_x, SO_x	1 m (Raw Sample), DC, CDP, plume	**x**	**x**
Non-Dispersive Infrared (NDIR) Analyzer (CA 602P)	Diluted Sample CO_2	1 m (probe-tip or two-stage dilution), DC, CDP, VPS, VPR, plume	**x**	**x**
Sunset Model 3 Semi-continuous ECOC Carbon Analyzer	Elemental & Organic Carbon	DC,CDP, plume	**x**	**-**
Gravimetric Analysis	Time-Integrated Total PM	DC, CDP, plume	**x**	**-**
Ion Chromatography	Time-Integrated SO_4	DC, CDP, plume	**x**	**-**
Pulsed Fluorescence Analysis	SO_2	DC, CDP, plume	**x**	**x**
Micro-soot Sensor (AVL Model 488)	Black Carbon	DC, CDP, plume	**-**	**x**
Engine Exhaust Particle Sizer (EEPS TSI 3090)	Particle Size Distribution	DC, CDP, plume	**-**	**x**
FID Analyzer (CA 600)	Total Hydrocarbons	DC, CDP, plume	**x**	**x**

5.1 T63 ENGINE DEMONSTRATION SETUP

Three sampling probes (two raw sample probes and one diluted at probe-tip) were installed at the exit of the engine exhaust extension pipe to collect samples for distribution to several systems or instruments (Figure 5). Both raw sample lines were heated to 150°C consistent with the SAE ARP1256 guidelines for gaseous emissions [6]. Raw sample was provided to a carbon sampler to collect samples for organic and elemental carbon analysis or to a Multi-Angle Absorption Photometer (MAAP) for black carbon mass concentration measurement. A second raw line provided sample for gaseous emissions measurements and to the DC or CDP. The line lengths between instruments and sample location for the devices and plume were similar to ensure equivalent particle losses for valid comparisons of PM emissions. The plume was sampled with a 3.8 cm diameter probe port installed at the same height and at 4 m from the engine exhaust tube. All research groups were provided diluted samples from either from the DC, CDP, or the plume probe. Air Force Research Laboratory (AFRL) also analyzed the tip-diluted sample representing the “non-volatile” PM emissions.

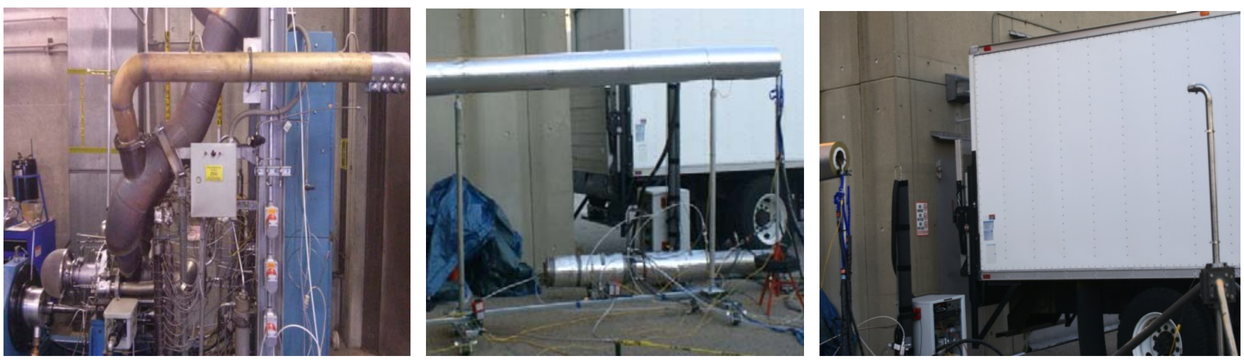

Figure 5. T63 Engine with Extension Pipe to Direct Exhaust Outside of the Test Cell for Exhaust Sampling with Tip-diluted and Gas Probes at Pipe Exit and Large Gas Probe at Plume

5.2 C-17 (PW-F117 ENGINE) DEMONSTRATION SETUP

The emissions sampling system used in the C-17 aircraft engine consisted of four ganged gas probes which collected engine exhaust raw sample for distribution to the condensation devices, VPS and instruments. The probes were installed ~42 cm from the engine exit plane, with the top probe was positioned at the center of the engine. The rake was mounted on a heavy-duty steel structure restrained with three tanks of water (~3,400-kilogram total weight) to prevent movement during engine operation. Two plume probes, installed at 10 and 20 m from the engine exit plane, where used to sample the plume at the two locations. The plume probes had 19.0-millimeter diameter ports and where placed at approximately 3 m height from the ground (engine center was at 5 m) to collect well-mixed engine core/fan diluted samples. Initial tests showed that only engine fan (bypass) air was sampled through the 10-m probe due to its relatively close proximity to the engine, thus, only the 20-m probe was used for plume measurements. Samples from the DC, CDP and plume were sampled and evaluated individually and isolated from the instruments using remotely actuated ball valves. Probe setup, sample lines and position of the mobile laboratories are shown in Figure 6.

Figure 6. Emissions Mobile Laboratories, Plume Probe Setup and Emissions Probe Rake at Engine Exit Plane during C-17 Aircraft Engine Emissions Demonstration

6.0 PERFORMANCE ASSESSMENT

PN, size distribution, mass, and chemical composition were measured for samples extracted at the engine exit plane, at the exit of the dilution devices and at the far field location. General metrics or indicators of effective performance of the dilution devices and the VPS are listed in Table 4.

Table 4. Systems Performance Criteria

Demonstration Device	Measurement	Metric (compared to designated non-volatile PM)
VPS	• Non-volatile PN	• PN (±15%)
	• Non-volatile Particle Size	• Similar size (±15% of mean diam.)
	• PM chemical composition • Elemental Carbon/Organic Carbon (EC/OC) National Institute for Occupational Safety and Health (NIOSH) 5040	• OC reduction (>70%) ▪
	• Modified PMP validation	• Evaporation of >99% tetracontane 15 nm particles
DC and CDP Total PM	• PN	• Increased PN (10X)
	• Particle Size Distribution	• Evidence of nuclei PM formation (10X in 5-20 nm range)
	• Particle Mass	• Increased mass (>30% depends on fuel composition and volatile PM)
	• Non-volatile chemical composition	• Increased organics in non-volatile fraction (>30% depends on fuel composition and volatile PM)
	• EC/OC NIOSH 5040	• Increased organic fraction(>30% depends on fuel composition and volatile PM)
DC Non-volatile PM	• PN • Particle Size • Particle Mass	• Similar PN (±25%) • Similar size (±15% of mean diam.) • Similar Particle Mass (±25%)

Specific details for each demonstration and data collected by the individual teams are discussed in the following subsections. Performance assessments of the condensation devices and VPS relative to the success criteria described in Table 1 are discussed.

6.1 DEMONSTRATION ON T63 ENGINE

Engine test conditions for the demonstration of the devices on the T63 engine were shown in Table 2. Raw samples were taken at the engine exit (extension pipe) and transferred through heated sampling lines at 150°C to the DC, CDP and gas emissions instrumentation. The dilution ratios in the condensation devices were controlled to match and double the sample dilution measured in the plume probe. Doubling the dilution ratio was performed to investigate if volatile PM were promoted with increased dilution. As previously noted, the plume probe was installed relatively close to the engine exhaust extension tube Make them exit to obtain a strong PM signal while sufficiently far to promote volatile PM nucleation. Infrared signals of the engine exhaust plume at the exit tube and near the plume probe for each condition were very strong near the exit tube, but weak near the plume probe due to the rapid mixing of engine gases and air, and the low velocity exhaust from the turboshaft engine. It is noteworthy that the low momentum of the exhaust gases combined with the erratic ambient air recirculation flows near the exhaust pipe (due to its proximity to the facility structure and architecture) produced very complex flows at the plume, which deviates from the characteristics of turbofan exhaust flows. Thus, it is recognized that these exhaust flows or plumes are not representative of typical turbine engines exhaust, but provide insight into the gas-to-particle transformations in the plume and comparisons with those processes in the condensation devices. After entering the probe, the plume sample was drawn into a mixing tunnel (to enhance mixing of ambient air and engine exhaust) where the sample was drawn into the instruments via internal or external pumps. Three fuels with varying concentrations of aromatics and sulfur were used during the demonstration to vary the concentration of volatile PM formed. The fuels used included: a conventional low sulfur and aromatic JP-8 (40 ppmw and 11% by w respectively), the JP-8 doped with a blend of aromatics to increase concentration to 25% by vol and the JP-8 doped with an organosulfur compound, *tetrahydrothiophene* (C_4H_8S), to increase its sulfur content to the maximum (although very unlikely) sulfur content in jet fuel of 3000 ppmw.

6.1.1 Summary T63 Engine– Measurements at Plume, DC, CDP and Exit

- Increased particle concentrations (mostly nvPM) were measured at both engine conditions with all sampling techniques with engine fueled with the aromatic-doped fuel.
- Particle concentrations in the plume were significantly higher (4-11X) than at the exit plane especially at idle and with the high sulfur fuel due to the higher concentration of organics (i.e., unburned hydrocarbons) and sulfates respectively. Smaller relative increases were observed for cruise due to the lower concentration of organics and increased exhaust velocities, which reduced residence times for the formation of volatile PM.
- Negligible impact of fuel sulfur content on engine Particle Number Emission Index ($EI_{n)}$ for samples diluted at the probe-tip, further demonstrate that tip-dilution only measures non-volatile PM.
- PM samples conditioned through the CDP and DC yielded significantly lower nvPM than the plume samples, and doubling the dilution ratios in the CDP and DC to those found in the plume did not encourage further nucleation of volatile PM.

- The CDP and DC are shown to promote volatile PM formation as compared to the tip-diluted sample. Nuclei size particles (assumed to be 7-23 nanometer [nm]) increased by a factor of at least four in the DC for both engine conditions; however, these increases were significantly lower than those observed in the plume. **Based on these data, the success criteria for the condensation devices (10X increase in PM nuclei size concentrations relative to probe-tip dilution) were not achieved.**
- The DC diluted with nitrogen produced lower (~30-45%) particle concentrations than for tip-diluted samples, thus, **the success criterion of ±25% of the tip-diluted sample was not met.**
- The plume sample typically measured higher organic-to-black carbon (OC/BC) ratios than the DC and CDP. This effect was more pronounced at idle power.
- The DC generally produced higher SO_2 EIs than the plume and CDP for all fuel types at idle. However, for JP-8S at idle the DC EI values were comparable to those from the plume.
- For particles with diameters ≤15 nm, which are generally considered to be volatile, the removal efficiency for both PMP VPR and VPS was statistically 100%.

6.2 DEMONSTRATION ON C-17 (PW-F117) ENGINE

Test conditions for the demonstration of the devices on the C-17 aircraft (PW-F117 engine) were shown in Table 2. The demonstration was conducted with F-24 jet fuel, a Jet A plus military additives. The fuel was an average jet fuel in terms of physical and chemical properties with very low sulfur (20 ppmw). Low engine power settings were selected for the demonstration as these are the most prone to high volatile PM formation due to the higher concentration of organics (unburned hydrocarbons) in the exhaust. Raw samples collected from the engine exit through four gas probes were transferred through heated sampling lines at 150°C to the Dekati ejector ("non-volatile" PM), DC, CDP and gas emissions instrumentation. The total dilution ratio (DR) (ejector plus secondary) for the non-volatile PM sample was between 6:1 – 20:1 for most cases. For the volatile PM samples, the DR in the condensation devices were controlled to match the sample dilution measured in the plume (20 m) probe. These varied based on engine power as follows: DR=~32:1 at idle, DR= ~25:1 for 20% max thrust and DR= ~21:1 for 33% max thrust. The DR in the CDP was varied by controlling the total nitrogen dilution flow, while in the DC the secondary dilution (air) was adjusted while maintaining constant nitrogen flow to the ejector.

Due to the limited aircraft availability (445th Airlift Wing reserve unit mission commitments), this demonstration was limited to one full day of testing. Although a second test day was planned, adverse weather (i.e., strong winds, rain, thunderstorms) limited the demonstration to only a few hours on day two. Unfortunately, this severely constrained the number of tests and variables considered, which hindered the ability to fully demonstrate the devices. Potential sample leaks through a sampling system fitting for tests at engine idle, very likely affected the magnitude of the measured PM parameters; however, it is believed that it did not impact the trends of the data and conclusions of the demonstration.

6.2.1 Summary PW-117 Engine– Measurements at Plume, DC, CDP and Exit

- Very good agreement for NOx and CO emissions observed between the International Civil Aviation Organization (ICAO) database and this campaign, demonstrates that a representative engine core sample was analyzed.

- At idle, the plume sample shows significant increases in particle concentrations compared to tip-diluted samples demonstrating formation of volatile PM.
- A shift in the size distribution to smaller mean particle sizes is also observed in the plume, which is evidence of formation of volatile particles.
- Comparisons of the DC to the tip-diluted sample, also shows increases in PN and shift to smaller particles but at a much lesser degree compared to plume samples.
- The CDP conditioned sample had slightly fewer particles than the tip-diluted sample and slight shift to smaller diameters. This could be related to increased particle losses in the CDP.
- Figure 7 shows the concentration of nuclei particles (7-23 nm diameter) for the four sampling techniques employed during the demonstration. **Although there is evidence of volatile PM formation, neither condensation device met the success criteria of an order of magnitude increase in the volatile PM concentrations relative to tip-dilution as stated in Table 1.**

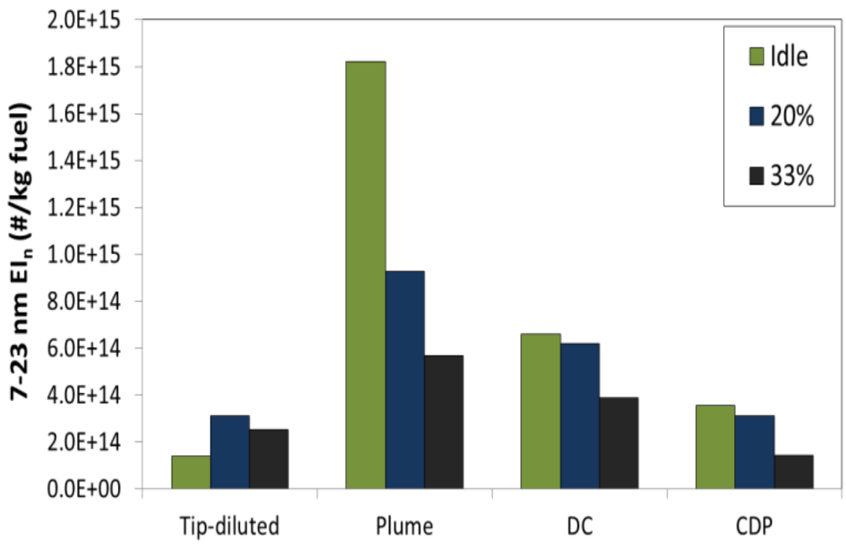

Figure 7. PN EI for "Volatile" PM Based on Nuclei Size Particles Measured with the Scanning Mobility Particle Sizer (SMPS)

- Excellent agreement in BC PM mass was observed for the DC and plume at the lower power conditions; however, the DC produce much higher PM than the plume at 33% power.
- It was determined that there is significant contribution of engine lubrication oil to volatile PM emissions for samples at the plume. More than 90% of the PM organics at all power settings was lubrication oil, which is also identified as Mobile II lubrication oil [7,8].
- After correcting the contribution from lubrication oil, it was observed that organic PM composition accounted for a very small portion of total PM mass (due to very low hydrocarbon emissions even at idle).
- Selected gas phase organics from the plume and condensation show the EIs measured at the plume are significantly higher than those observed for the DC or CDP.

- PM conditioning by either PMP VPR or VPS at 350°C, results showed a significant removal of particles. For engine idle, the particle removal efficiency by VPS is estimated to be 82.3%, and that for PMP VPR is 75.5%. For particles smaller than or equal to 15nm, the removal efficiency for VPS was found to be 100% and 93.6% for PMP VPR. The results showed that the VPS was as effective as the PMP VPR in removing particles for the entire size range. However, only the VPS performed reasonably for the 15nm particles with an efficiency greater than 99% as required by the performance criteria of this program.

6.3 TECHNOLOGY DEMONSTRATION PERFORMANCE SUMMARY

A summary of the performance objectives, success criteria and results of the demonstrations (as discussed in the previous subsections) are listed in Table 5. The results show the potential of the condensation devices to simulate gas-to-particle processes in the atmosphere; however, due to performance inconsistencies and that not all success criteria were met, it is concluded that the devices are not ready for compliance relevant measurements. The VPS demonstrated very high potential to remove volatile species for the measurement of only non-volatile PM and should be considered for engine certification measurements after further validation against the updated VPS requirements listed in the SAE ARP 6320 [9].

Table 5. Summary of Demonstration Objectives, Success Criteria and Actual Performance

Performance Objective	Success Criteria	Criteria Met?
Demonstrate volatile species condensation (volatile PM formation) in the DC and CDP. Significant increase in PM compared to probe-tip dilution.	Clear evidence of volatile particle formation in DC and CDP compared to probe-tip dilution.	**YES**
	10X increase in 5-20 nm PN	**NO**. Only 2-5X increase.
Demonstrate similar PM chemical characteristics for samples collected at the DC, CDP and 20 m locations.	Composition of PM from DC or CDP and 30 m sample within ±25% in absolute or normalized terms.	**YES**. Organic carbon EI_{mass} similar magnitude.
Demonstrate that ambient air diluted samples in the DC and CDP (N_2 dil) produce similar total PM characteristics as at the 20 m sampling location.	±40% of the PN	**INCONCLUSIVE** **YES** at higher engine power. **NO** at idle.
	±30% mass	**YES** at two lower conditions.
	±25% of mean diameter	**INCONCLUSIVE** **YES -** T63 engine tests. **NO -** C-17 tests. Larger concentrations of nuclei particles at plume with significantly reduced mean diameter but not matched with DC or CDP.
Demonstrate that N_2 diluted samples in the DC and CDP produce similar non-volatile PM characteristics as probe-tip	±25% of the PN	**INCONCLUSIVE** **YES** – T63 engine tests Not evaluated – C17
	±15% of mean diameter	**YES** – T63 engine tests Not evaluated – C17
Demonstrate efficient performance of the VPS to remove tetracontane particles	> 99 % vaporization of 15 nm tetracontane particles	**YES**
Demonstrate efficient performance of the VPS to remove volatile species from engine PM	Qualitative data. Significant reduction in 15nm and smaller particles and reduction on mean particle size	**YES.**

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7.0 COST ASSESSMENT

Although the performance of the condensation devices did not satisfy all the demonstration goals, an initial cost assessment for implementation is provided below in case a future program can continue the development of these devices and the performance goals are achieved.

7.1 COST MODEL

The successful demonstration of the PM sample conditioning devices and VPS, in concert with already accepted PM instrumentation, provides turbine engine manufacturers a methodology for measuring non-volatile and total PM2.5 emissions factors from military weapon systems, in a controlled environment. Current (non-standard) practices to measure total PM (i.e., far field) are complex, time consuming, expensive, and provide unstable data. Since there isn't an established alternative for a total PM measurement methodology, a cost comparison between the current and demonstrated methodology is difficult. However, based on current practices, the demonstrated methodology is expected to significantly reduce testing and logistics costs by using existing gas probes and reducing the required set up and actual engine run times. The cost comparisons below are based on the present cost of current practices and the demonstrated approach.

7.2 COST ANALYSIS AND COMPARISON

For the characterization of only non-volatile PM, the VPS will lead to significant savings in equipment costs to remove volatile species from the PM sample. The volatile particle remover (VPR) system currently considered by the SAE E31 committee for non-volatile PM sample characterization is manufactured by AVL and costs approximately $250K. The VPS in this project is estimated at a much lower $55K, and allows analysis of the volatile fraction. Table 6 shows a comparison of estimated costs between the current practices and the technologies demonstrated in this project. The long-term savings are realized in the test costs at approximately $85K less per test for the demonstrated technologies.

Table 6. Type of Cost and Cost Comparison for Current and Demonstrated Technologies

Demonstrated Technology Costs		**Current Process Costs**	
Activity	**Avg. Cost ($k)**	**Activity**	**Avg. Cost ($k)**
Equipment		**Equipment**	
- **DC**	50	- Volatile Particle Remover	250
- **CDP**	50	- Black Carbon Instrument	50
- **VPS**	55	▪	
- **CPC**	60	- CPC	60
- **Particle Sizer**	75	- Particle Sizer (2)	150
- **Particle Mass Instrument**	100	- Particle Mass Instrument (2)	200
- **Sampling System**	100	- Sampling System	150
- **Gas Emissions Instrumentation**	200	- Gas Emissions Instrumentation	200
- **Probe System**	75	- Probe Systems	85
Test Costs		**Test Costs**	
System Installation & Teardown	40	System Installation & Teardown	50
Near Field Testing	80	Near and Far Field Testing	130
Data Analysis	40	Data Analysis	65
Other (travel, supplies, misc.)	30	Other (travel, supplies, misc.)	30
Total	**955**	**Total**	**1420**

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8.0 IMPLEMENTATION ISSUES

The demonstrations in this project showed that the two condensation devices to promote volatile PM formation in turbine engine exhaust did not meet all of the performance criteria set for the program. Although both the DC and CDP showed potential, as evidenced by the formation of PM from volatile species, these were not sufficient to fully simulate the thermo-physical processes in the atmosphere which lead to the formation of volatile PM and PM with characteristics of those found in aircraft engine plumes. However, as mentioned previously, the demonstration on the turbofan (PW-F117) engine was very limited, which precluded the adjustment of dilution parameters that could have improved PM data agreement between plume and devices. If further work is performed and improved performance can be demonstrated, the implementation issues for turbine engine OEMs are relatively minor since the sampling system from engine to device is the same as those existing for gaseous emissions and smoke number certification of engines. Additions include the dilution device, sampling lines for the sample after conditioning, and the PM characterization instruments.

The VPS met the success criteria based on its comparison to the PMP VPR performance using C_{40} and turbine engine particles. Implementation issues are minimal and believed to be simpler than the use of the VPR systems considered presently by the SAE E31 committee.

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